Title: Economic Impacts Caused by the Failure of a Maritime Global Critical Infrastructure – A Case Study of Chemical Facility Explosion in the Straits of Malacca and Singapore

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Abstract

Globally shared and intensively used maritime infrastructures such as ports and straits have the potential to cause trans-boundary and multi-sector impacts on our society in case of disruption. This type of infrastructure can be called a “maritime global critical infrastructure (MGCI)”; its disruption can be caused by various types of hazards. IRGC (2011) was first to focus on this issue, identifying critical deficits of risk governance in an MGCI and making recommendations for improvement. However, a detailed impact assessment of a major disruption to an MGCI has not been fully conducted due to various factors including the complex interrelations and mechanisms of MGCI activities and processes and their cascading impacts, the limited availability and difficulty of access to the necessary data sets at regional and global scales, the need to combine modeling approaches from various fields.

In an effort to overcome some of the above challenges, this paper presents the results of a prototype economic impact assessment of an MGCI disruption scenario. The Straits of Malacca and Singapore have been selected as a representative MGCI, and an oil refinery fire and explosion in the Singapore Strait as an initiating disruption event. The impact assessment and associated sensitivity study presented here, including the scheme of price changes as a result of the increase of transportation costs, reveal the value of the Straits and ports and the requirements of a relatively fair governance scheme.

Key words: maritime transportation, global critical infrastructure, technological disaster, economic impact, risk assessment

1. INTRODUCTION

Increases in worldwide energy demand and industrial supply-chain systems among different countries have led to our society becoming increasingly dependent on international maritime and air shipping services. In particular, international hub ports and straits, where greater numbers of ships, airplanes and their handling cargos are concentrated than anywhere else, are regarded as potential choke points: i.e. the disruption of services at such points can cause enormous and complex impacts on global economic activities. These international hub ports and straits are regarded as so-called “global critical infrastructures” and intensive efforts are required to ensure their safety. International straits such as the Straits of Malacca and Singapore and the Suez and Panama Canals, which have certain limitations of traffic capacity, can be thought of as representative infrastructures and there is a need to enhance security and disaster mitigation levels based on risk assessments of these representative areas. Based on the work presented in IRGC (2011), a maritime global critical infrastructure (MGCI) can be defined as systems and assets as they relate to marine activities specifically and have the capacity to impact international security, global economic security, public health or safety, or any combination of these.

An inherent characteristic of global critical infrastructures is that they will involve various stakeholders worldwide. The successful involvement of those stakeholders as well as the identification and quantification of trans-boundary risks are key issues for constructing burden-sharing schemes for risk reduction. Another important aspect of global critical infrastructures is that they are subject to a growing trend of increasingly complex risk. That is, the risks associated with global critical infrastructures can evolve as the concentration of economic activities and supporting infrastructures develops. For example, an increase in heavy vessel traffic might make ship collisions more likely, and densely located oil facilities along the coastlines might result in cascading impacts on adjacent facilities. These types of concentrations tend to create benefits as an efficient economic system, but, on the other hand, fewer investments are made in other alternative infrastructure systems.

Renn and Walker (2008) discussed a global risk governance scheme for general risks including complex and interconnected infrastructures such as MGCIs. They discussed how their risk governance framework could be applied to such a risk and demonstrated several case studies. Essentially, their risk governance framework is composed of phases of pre-assessment, risk appraisal, tolerability & acceptability judgment and risk management. Each phase and its contents are closely interlinked through communication among the stakeholders related to each relevant issue. According to this comprehensive risk governance framework, MGCIs were still in the early stage of risk governance just a few years ago and were in need of more intensive pre-assessment and risk appraisal to characterize the associated risks.

IRGC (2011) focused on the Straits of Malacca and Singapore as a case study for the development of commonly recognized risk scenarios and the identification of risk governance deficits based on the results of several multi–stakeholder workshops[1]. The risk scenarios identified as having the potential to result in a blockage of the straits, based on pre-assessments conducted by participants, were ship collision, chemical facility explosion and fire and cyber attack. The following remarks are part of the report findings and are described as part of identified risk governance deficits: “A fundamental risk governance deficit in the Straits comes from the fact that transit passage through the Straits is an international right that shall not be impeded under international law, but the costs of organizing

[1] The workshops were held in 2009 and 2011. Participants were from littoral states and user countries in Asia, including persons from central/local governments, shipping companies, universities and private research institutes. More details are given in the IRGC study (IRGC 2011)

governance mechanisms and of maintaining and upgrading infrastructure to ensure safe, secure and sustainable usage are externalities to those who use the Straits." [p.39]. This identified deficit focus on the importance of assessing externalities related to the Straits, which are likely not related to only a single stakeholder.

Assessing economic impacts caused by the disruption of MGCI is one of the approaches to understand one aspect of such externality. For example, it is the good example that Sullivan (2010) addresses the importance of the Horn of Africa in terms of the supply chain impacts due to piracies. The result gives a rough image on how much who should pay for safety investments against piracy. The work presented in this paper also puts focus on externality of MGCI in terms of economic impacts of its disruption, which was touched but not sufficiently discussed in IRGC (2011), especially in terms of global impacts. Quantitative risk assessment of MGCI is achieved by integrating a global economic impact model and a technological hazard estimation model. Thus the paper would provide a prototype interdisciplinary case study for MGCI. Specifically, the example of an oil refinery explosion and fire in the Singapore Strait is identified here as a disruption scenario for the Straits of Malacca and Singapore. An application of the models to the disruption scenario reveals the value of the Straits and Port as well as the distributed economic damages incurred by stakeholders, which is an important input to the discussion of requirements for a relatively fair governance scheme.

2. HAZARD IDENTIFICATION AND ECONOMIC IMPACT STUDIES IN THE STRAITS OF MALACCA AND SINGAPORE

2.1 About the Straits of Malacca and Singapore

In this study we focus on the Straits of Malacca and Singapore (herein “the Straits”) and the Port of Singapore. This is one of the most congested areas in the world in terms of maritime transportation. Most of the sea routes connecting Europe and East Asia are obliged to pass thorough the Straits and the number of vessels passing through continues to increase, from 55,957 in 2000 to 74,133 in 2010 (JAMS 2011). This upward trend throughout the decade includes increases in VLCCs[2] (from 3,163 to 4,333), Bulk Carriers (from 4,708 to 11,642) and Container Ships (from 18,283 to 24,806). According to Containerization International (2010), the Port of the Singapore handled 29.92 m TEUs[3] in 2008 and is ranked first in the world for cargo. The closure or functional failure of the Straits or their port facilities has the potential to cause significant impacts on global economic activities, and as such both the Straits and their port facilities are considered to be global critical infrastructures. As described in Fig. 1, there are alternative sea routes to the Straits, which pass thorough the Sunda and Lombok Straits. However, it normally takes a greater number of days and navigation support infrastructures are not adequately installed in comparison to the Straits of Malacca and Singapore.

The importance of the Straits is widely recognized by those littoral countries (Singapore, Malaysia and Indonesia) which directly maintain the function of the Straits, international organizations (e.g. International Maritime Organization (IMO)) and user countries (e.g. Japan). Efforts have been made by the littoral countries and other stakeholders to avoid incidents such as ship collision, piracy attacks and oil spills. These efforts include, for example, the traffic separation scheme (TSS) for avoiding collisions between westbound and eastbound ships, navigational aid infrastructures (e.g. charts, beacons) for detecting shallow water channel points, and an information system (known as

[2] Very Large Crude Oil Container: between 200,000 and 300,000 DWT (Dead Weight Tonnage)

[3] Twenty-foot equivalent unit (TEU) is a unit of cargo capacity used to describe the capacity of container ships and container terminals based on the volume of a 20-foot-long (6.1 m) metal container.

STRAITREP) for identifying ships' attributes such as ownership and country as a passport-type security check.

However, as is mentioned in the previous section, global critical infrastructures present major risk governance challenges due to trans-boundary risks inherent in complex systems both in infrastructures and socio-economic activities. The risk assessment itself remains an important issue for global critical infrastructures. Nevertheless, the need to develop a prototype methodology remains. The results obtained may provide a relatively concrete image for all stakeholders to share concerns and become better prepared for any accidents and disasters.

Fig. 1 Locations of Straits of Malacca and Singapore

2.2 Previous Studies on Hazard and Economic Impact Assessment

2.2.1 Hazard Assessment

Several hazards can be assumed around the Straits of Malacca and Singapore. These hazards include natural disasters, oil spills, ship collisions, piracy, and terrorism, and combinations thereof. For example, Hong and Ng (2010) focus on the growing concerns of piracy and terrorism and point out the deficits of current international legal instruments. Bryant (2001) reviews historical tsunami disasters around the world, and describes the severe damage caused by the tsunami disaster in Indonesia. More investigation is needed on the tsunami risk around the Straits as well as other natural disaster risks, but because the Straits are surrounded and protected by islands, it is less likely that the impact of tsunami would be too severe on the Straits. In IRGC (2011), these possible hazards around the Straits are reviewed and summarized and three characteristic hazard scenarios are adopted: ship collisions, cyber attacks, and chemical facility explosion and fire.

Ship collisions are considered the most frequently occurring scenario under the considerably congested conditions of the Straits. A typical ship collision model has also been reviewed by Li et al. (2012), but the likelihood of such a collision blocking the Straits for an extended period is estimated to be low. Cyber attack is one of the emerging risks which can target infrastructure systems. The scenario in the IRGC (2011) study is developed under the assumptions that port and ship operation systems are hampered. There is a possibility of collision due to malicious remote control, but the duration of the disruption to the Straits is not estimated to be as long as that seen in the chemical facility explosion and fire scenario. A chemical facility explosion and fire near the navigation channel would affect both the Straits and the ports resulting in a prolonged blockage of the Straits. Therefore, in this study the chemical facility explosion and fire scenario has been chosen. The details of this scenario are discussed in Section 3.

2.2.2 *Economic Valuation of the Straits of Malacca and Singapore*

There are a few studies regarding the economic value assessment of the Straits of Malacca and Singapore. One pioneering work, carried out by Morisugi et al. (1992), estimates the value of the Straits in terms of transportation costs. In this analysis, transportation costs are defined by ship rental fee and fuel costs and are compared between the Straits of Malacca and Singapore, and the Lombok Strait, one of the main substitutable routes. In case that all the ships were to pass through the Lombok Strait instead of the Straits of Malacca and Singapore, the consequent increase in transportation costs is estimated at $84.0bn from 1966 to 1985, with the largest cost increase ($24.0bn) resulting from the import and export of petroleum between the Indian Ocean and Eastern Asia. Considering a future projection of increasing vessel traffic, then, the increased transportation costs incurred through use of the Lombok Strait would have been approximately three times higher ($257.3bn) between 1990 and 2009. In addition, it is estimated that the export and import structure would have changed due to these cost increases, and that petroleum imports to the United States would have been reduced by 16% based on a model of the elasticity of substitution.

Shibasaki and Watanabe (2010) developed a shipper's and carrier's cost minimization-type model to determine route changes in case that the Straits of Malacca and Singapore were to be completely shut down. The model also takes into account both sea and inland traffic routes for ASEAN countries. The results of the model application show a reduction in cargo traffic in Malaysian Ports, whereas the Port of Singapore overtakes Malaysia in terms of cargo traffic, handling a larger amount of traffic.

The IRGC (2011) focuses on the impacts on the domestic economies of affected littoral states. The study assumes the loss of international shipping services from the littoral states due to damages both to port facilities and closure of the Straits. Based on a straightforward input-output analysis, the study estimated an economic loss of $18bn in the littoral states alone, assuming that the closure lasts for a year.

These studies illustrate a general picture of the importance of the Straits for both littoral states and user countries. The valuation methods adopted can vary and should be compared. What is important to note is that results are influenced by the type(s) of scenario(s) selected for analysis. The affected regions have to be identified and any infrastructures and artificial facilities, which could be damaged and could therefore expand damages, have to be carefully considered in each scenario. The recovery duration for damaged infrastructures can also affect economic impact scenarios.

2.3 Risk Assessment in this Study

Fig. 2 illustrates the risk assessment considered in and the primary focuses of this study. Hazard assessment is carefully examined from the perspective of the impacts on the availability of the Straits, port facilities, and the duration of functional damage. The focus of the paper is on long-term disruption as a worst case scenario, which includes relatively minor incidents, thus a certain level of preparedness and foresight among all the stakeholders is expected to have been in place for both minor and major incidents. A scenario of chemical facility explosion would have the potential to influence both the navigation route and port facilities for an extended period. More details of hazard scenario settings are discussed in Section 3.

Fig. 2 also describes what would likely occur as an economic consequence of the disruptions of the Straits and/or port facilities. The major targets of this study are either the long-term disruption of both the Straits and port facilities or of the Straits alone. In the case of the Straits of Malacca and

Singapore, “Substitution of sea route” indicates that other straits, such as the Lombok Strait, are used as an alternative sea route. “Substitution of port” (international shipping service) denotes the case in which the Port of Singapore cannot be used and other ports as well as shipping service companies may overtake the position (functions) of the port. These two results are likely to bring about an increase in transportation costs. The other problem is that the productivity of domestic industries may decrease. Firms have to consider substitutable methods for sea transportation, or shift to those industries which have less dependency on the affected port for production. Both a decrease in productivity and shipping service sales would affect local economies as well as the global economies which depend on goods from the affected country. The most likely scenario is that if these incident-chain disruptions were to last for a long period, the global economy would try to adjust to the situation by changing its trading pattern.

In order to analyze these sorts of economic impacts, one of the best approaches is to adopt a global economic model, such as an input-output modeling or a spatial computable general equilibrium modeling approach (SCGE). In recent years, the application of SCGE to the risk assessment of infrastructure disruption has been applied (Rose and Liao 2005; Tatano and Tsuchiya 2008). In addition, thanks to efforts made to bring together international production and trading data, such as through the Global Trade Analysis Project (GTAP) (Hertel 1997), a global SCGE model is available for policy analysis. For example, Bosello et al. (2012) conducted an assessment on global economic impacts caused by sea level rise and derive from that assessment an analysis of the effectiveness of countermeasures. However, applications are still limited in the natural and technological risk assessment area and model setting procedures and the characteristics thereof are not well discussed. Our study later also provides potential applicability or benefits of global SCGE model to the MGCI problem by conducting several sensitivity analyses. It is shown that several preparedness and policy related parameters, such as swift change of supply chains and shipping company's pricing strategies, can affect the global impacts. For developing the global economic model for MGCI, efforts are also paid to estimating the transportation costs associated with detouring during the accident.

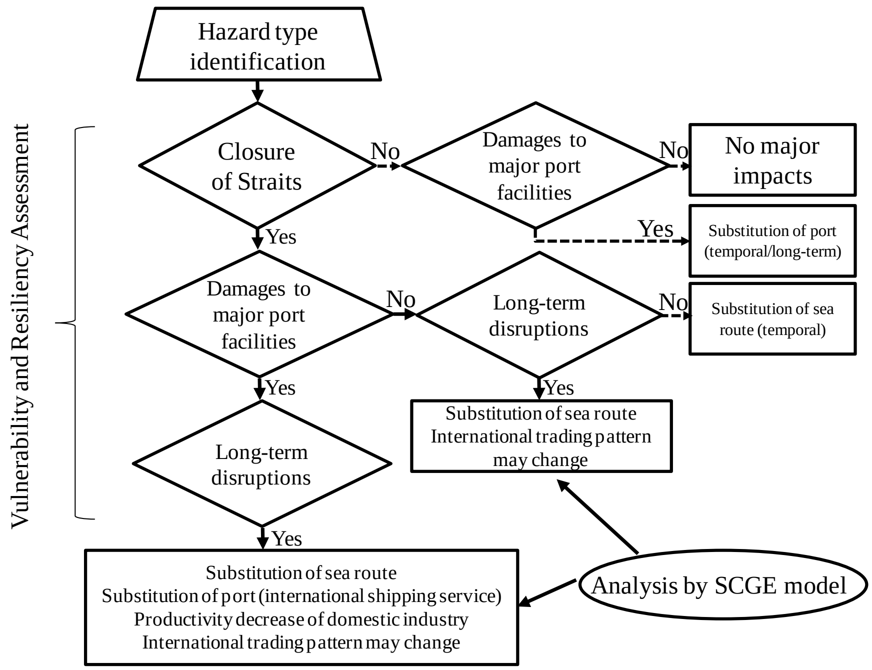

Fig. 2 Framework of Risk Assessment and Primary Focuses (Solid Arrows) in this Study

3. HAZARD SCENARIO DEVELOPMENT: CHEMICAL FACILITY EXPLOSIONS

Chemical and petrochemical facilities that handle large volumes of hazardous materials pose a threat to navigation if a large accident were to occur in the form of an explosion, oil spill or toxic gas release with major offsite consequences. First, a preliminary risk assessment of potential explosions and toxic gas releases from major industrial establishments located along the Straits was carried out. Then, possible scenarios of combined chemical accident and navigation channel disruption along the Straits were discussed. Of particular interest were facilities located on or near any of the six navigation choke-points along the Straits identified by the Maritime Institute of Malaysia (MIMA)[4] as shown in Fig. 3.

There are over 100 important global petroleum, petrochemicals and specialty chemical companies on the reclaimed Jurong Island alone (EDB 2010), which is located near choke-point 5 in the Singapore Strait. These companies own and operate facilities on the island and share common infrastructures and services. Other islands, including Seborak, Sambu, and Pulau Busing, have infrastructure for the storage of bulk liquids and gases. The delivery of products and prime materials from one island to another is possible via physically interlinked infrastructure. For example, the Shell mono-ethylene glycol plant on Jurong Island receives ethylene via a subsea pipeline from another ethylene and petrochemicals complex located across the navigation channel on Pulau Bukom island (Shell 2010). Natural gas from Indonesia's West Natuna field arrives at Jurong Island via a 640km undersea pipeline (IRGC 2011). Several data sources (EDB 2010; Shell 2010; Chemicals Technology Industry Projects 2010; Vopak 2010) were used to obtain industry information including industry-type, production volumes, and types and quantities of chemicals stored and processed.

4 This is given by the figure in keynote presentation by Ibrahim, H.M. at the International Workshop on Risk Governance of Maritime Global Critical Infrastructure, Kyoto University, June 4-5

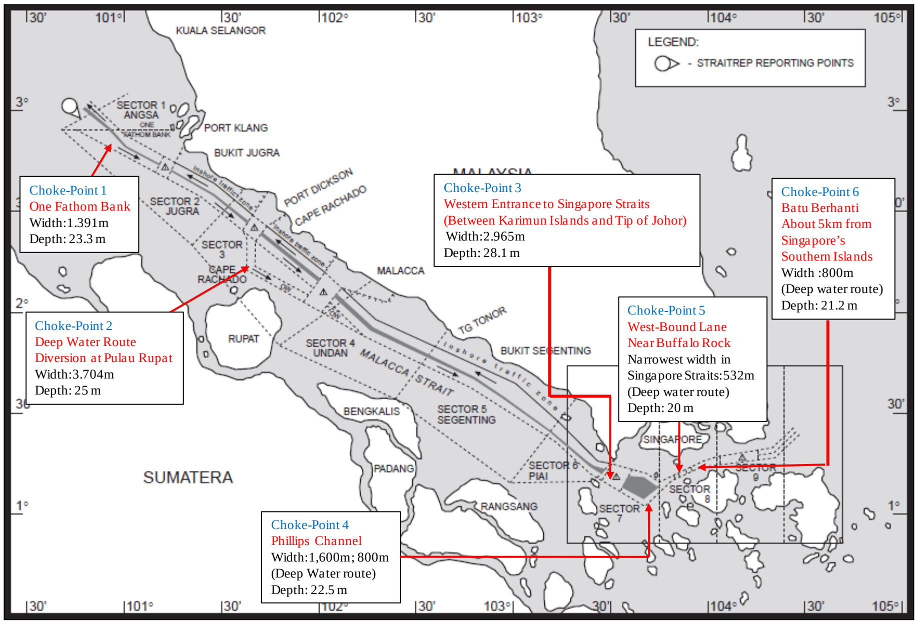

Fig. 3 Choke-points in the Straits of Malacca and Singapore(MIMA), identified based on Singapore Vessel Traffic Services (VTS)(Singapore VTS. STRAITREP, World VTS Guide 2007). MIMA identified six navigational choke-points. Disruptions in these zones could trigger cascading impacts throughout the global trade network and affect not only local coastal economies but also economies and societies elsewhere in the world.

Satellite pictures and other sources were consulted to determine storage tank distribution and storage tank diameters. Maximum storage quantities were estimated using typical height to diameter ratios for large atmospheric horizontal storage tanks, and assuming tanks were filled to 75% capacity (Austin 1988; Sinnott 1989). Similar estimates were derived for those spherical storage tanks observed. Furthermore, it was possible to assume the types of chemicals present including prime materials, intermediate and final products, working from a typical distribution of the various processes involved in the different types of industry, although exact location could not necessarily be established.

With this information and freely available accidental chemical release modeling software such as ALOHA (EPA 2007) and RMP*Comp (EPA 2001), accidental releases of toxic and flammable chemicals at these facilities were modeled and the areas that could be impacted by such releases were mapped. Table 1 shows the modeling results of the potential consequences of an explosion and a toxic gas release for a sample of industrial facilities (names have been omitted to protect identities). The table shows the estimated maximum distance to a 1 psi overpressure (d-explo) and the maximum distance to a toxic endpoint (d-toxic) assuming a 10 min (or instantaneous for explosions) release of the total contents of the tank and the unavailability of mitigation measures. The distance from the largest storage tank to the deep water channel (d-deep) for each facility is listed in the last column. Furthermore, Table I provides information on the location and the number of large storage tanks and the volume of the largest vertical and spherical storage tank at each facility.

Table 1 Modeling results of the potential consequences of an explosion and a toxic gas release for a sample of industrial facilities in the Straits of Malacca and Singapore (d-explo = maximum distance to a 1 psi overpressure; d-toxic = maximum distance to a toxic end point; d-deep = distance to the deep water channel.

ID	Location	No. of tanks	Vertical tank volume (m^3)	Spherical tank volume (m^3)	d-explo (km)	d-toxic (km)	d-deep (km)
a	Pulau Bukom	197	64,644	3150	< 1	> 25	0.5 – 2.0
b	Pulau Sebarok	79	56,000	n/a	< 3	> 25	0.5 – 2.0
c	Singapore	268	56,000	n/a	n/a	n/a	> 7.0
d	Jurong Island	> 100	56,000	25,000	< 4	> 25	> 7.0
e	Jurong Island	108	17,400	n/a	n/a	> 25	0.5 - 1.5
f	Melaka (Malacca)	> 93	50,000	13,300	< 3	< 6	> 20.0

Although it would require site-specific information to know where a particular chemical is stored, it is safe to assume that the identified chemicals are present at the relevant facilities, and could, therefore, be accidentally released. The center of each facility was chosen as the location of the point source. Mapping of the impact radius of the possible chemical accidents along the Straits and their six choke-points allowed the identification of chemical accident hotspots. Fig. 4 shows the maximum distance to a toxic end point for toxic gases, and the estimated maximum distance to a 1 psi overpressure, respectively, near the two accident hotspots identified: choke-points 4 and 5 along the navigation channel in the Strait of Singapore.

Fig. 4 Impact radius for toxic releases along the Singapore Strait. The yellow circles indicate the maximum distance to the toxic endpoint (e.g., chemicals including ammonia anhydrous, hydrogen sulfide anhydrous, hydrogen fluoride anhydrous). Prevailing winds will determine the direction of toxic plume hazard.

The likelihood of any of the above scenarios occurring as a result of human error or process upset was considered relatively low due to the safety and mitigation measures put in place by industrial facility owners/operators to prevent major accidents. Nonetheless, the history of the petroleum, petrochemical and chemicals industries shows that such accidents do occur and often with catastrophic consequences (Mahoney 1997; Garrison 2002; Fewtrell and Hirst 1998; Kourniotis et al. 2000; Steinberg and Cruz 2004; Chang and Lin 2006; USCSB 2007a, b, 2010). The BP oil spill in the US Gulf of Mexico which started on the evening of 20 April 2010 and took 87 days to contain demonstrated what can happen when failures in several safety and mitigation barriers align to allow the initiation and escalation of an accident (BP 2010). Furthermore, the potential for Natech (natural hazard triggered chemical accidents) accidents cannot be dismissed given the region's susceptibility to earthquake and tsunami hazards.

4. ECONOMIC IMPACT ASSESSMENT ON THE CASE OF AN EXPLOSION SCENARIO

4.1 Domestic and Global Economic Impact Assessment Based on the Spatial CGE model

4.1.1 Basic Structure and key parameters for MGCI analysis

GTAP Global Trade Analysis Project) (Hertel 1997) has initiated diverse analyses of world economic transactions under distinct types of exogenous shocks and is one of the most reliable databases and models in this area. Roughly speaking, there are two major functions in the model. One is the utility maximization of regional households and the other is the cost minimization of industries. Equilibrium is achieved as a result of these two optimization behaviors. Regional household utility maximization determines the consumption and savings of households and government as well as the investments of global banks based on their utility functions.

The behavior of the industrial sector significantly affects the results of the following case study. Essentially, the structure of production, given in Fig. 5, determines the behavior of the industrial sector. In the production function, four different types of constant elasticity of substitution (CES) function are used, and a representative CES functional form in case of two factor inputs can be expressed as:

$$Y = \alpha \left[\beta X_1^{\frac{1-\sigma}{\sigma}} + (1-\beta) X_2^{\frac{1-\sigma}{\sigma}} \right]^{\frac{\sigma}{1-\sigma}}, \quad (1)$$

where Y : Production output, X_1, X_2: Input, σ: Substitution parameter, α : Efficiency parameter, β : Distribution parameter. Basically, as the value of σ increases, either X_1 or X_2 can be substituted more easily by X_2 or X_1. The Leontieff function is a special example of the CES function, where the substitution parameter is set at 0. The bottom-most layer of the CES function in Fig. 5 indicates a selection of goods from various countries (or regions). Then, composite foreign goods are combined with domestic goods to produce composite intermediates. Furthermore, land, labor, and capital are also major production sources and produce added value. At the top layer, the composite intermediates and added value become inputs of the Leontieff production function. The parameters and related variables in bold/underlined fonts are highlighted as primal sources of impacts (exogenous shocks) in the case study and are explained later in more detail.

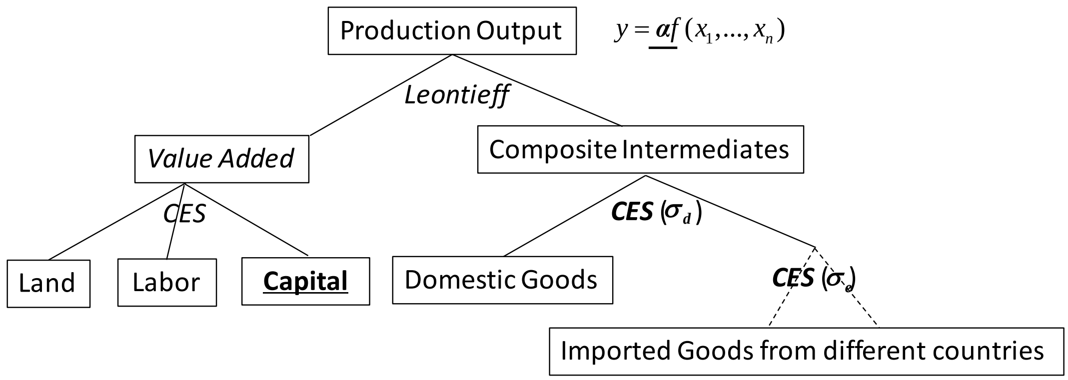

Fig. 5 Structure of Production Function

4.1.2 Settings of Countries Affected and Shocks Caused by Chemical Facility Explosion

Basic settings of regions and industrial sectors used in the case study are summarized in Tables 2 and 3, respectively. Those countries in East Asia assumed to be closely connected to the Straits of Malacca and territorial countries in South Asia are split into single countries, and the remaining countries are more roughly aggregated. A representative port in each region/country is described in terms of the annual volume of containers handled at the port. The Port of Singapore is ranked in first position according to 2009 statistics. The representative sea routes between countries/regions have been estimated based on the location of representative ports. Industrial sectors have been aggregated into 13 sectors, 12 of which are sectors producing trading goods, in which transportation sectors are subdivided in order to examine the effects of the impacts on the sea transportation sector. “Capital Goods” refer to those non-tradable goods which are resources used for producing capital in the respective countries/regions. Endowments are divided into five categories and are allowed to shift/move among sectors, but not among regions/countries.

Table 2 Selected regions and major representative ports with handled container volume

Region	Abbreviation	Representative Port	Containers Handled in 2009 (TEUs)
Oceania	OCN	Sydney	1,784,017
China	CHN	Shanghai	27,980,000
Japan	JPN	Tokyo	4,155,988
Korea	KOR	Busan	13,452,786
Taiwan	TWN	Kaohsiung	9,676,554
Malaysia	MYS	Klang	7,970,000
Singapore	SGP	Singapore	29,918,200
Indonesia	IDN	Tanjung Priok	3,984,278
Rest of Southeast Asia	SEA	Laem Chabang	5,133,930
South Asia	SA	Jawaharlal Nehru	3,952,735
North America	NA	Los Angeles	7,849,985
Latin America	LA	Santos	2,674,975
European Union	EU	Rotterdam	10,800,000
Middle East and North Africa	MEN	Dubai	11,827,299
Sub-Saharan Africa	SSA	Cape Town	774,238
Rest of World	RW	-	-

Table 3 Classification of endowments, and tradable and non-tradable goods

Endowments	Abbreviation	Tradable Goods	Abbreviation
Land	Land	Grain Crops	GC
Unskilled Labor	UnSkLab	Livestock and Meat Products	LM
	SkLab	Mining and Extraction	ME
	Capital	Processed Food	PF
	NatRes	Textiles and Clothing	TA
		Light Manufacturing	LMnf
Non-Tradable Goods	Abbreviation	Heavy Manufacturing	HMnf
Capital Goods	CGDS	Utilities and Construction	Util_Cons
		Transport and Communication	TransComm
		Sea Transportation	SeaT
		Air Transportation	AirT
		Other Services (e.g. insurance)	OthServices

In the explosion scenario, the major focus is to establish how damages to the production system and cost increases in the sea transportation sector can be expressed in the model. As shown in the emboldened text in the production structure given in Fig. 5, this study stresses the characteristics of four key parameters. Simultaneous shocks are considered and several vital parameters are changed and tested as a sensitivity analysis.

Firstly, in the sea transportation sector, the efficient parameter α of the Leontieff function can be decreased if there is damage to port facilities. This will create a supply shock in sea transportation services, affecting not only the damaged country but also the rest of the world. CES parameters for intermediates, σ_d and σ_e, are also of research interest[5]. In the case of technological disaster, industries are not able to change suppliers as swiftly as they might under normal circumstances. This is because adjustment costs become expensive, particularly since companies will need to analyze the situation and look for alternative contracts while competing with many other companies facing a similar situation. The values of the parameters used in GTAP are obtained as a result of long-term adjustment. To reflect the particular conditions considered in this study, a sensitivity analysis on σ_d and σ_e was conducted by adopting half values of the default settings.

The assumption of capital movement among sectors and countries also affects the results. In particular, in a default model in GTAP, there is an assumed restriction of capital movement among countries but not among sectors in a single country. However, as discussed in the previous paragraph, this assumption does not hold true and the cases in which capital movement is allowed are simulated in the following sector. In GTAP, this adjustment can be conducted by changing the substitution parameters,

[5] The values range 3.8-11.8 for σ_e and 1.9-5.1 for σ_d .

since capital movement is also described in CES functional form.

On the other hand, a transportation cost shock (the reflection of detour costs onto international shipping prices) is described through a technical change of the sea transportation system. Here, transportation technology indicates an aggregation of cost reduction developments such as the reduction of vessel fuel consumption rate. In GTAP, the relationship between transportation cost and transportation technology is described as follows.

$$PT(i,r,s) = \overline{PT} - AT(i,r,s), \tag{2}$$

where $PT(i,r,s)$: Transportation cost per unit good of sector *i* from region (/country) *r* to *s*, $\overline{PT}$: Average cost of all the transportation cost, $AT(i,r,s)$: Technical status of transportation system. Therefore, all costs peculiar to the routes and goods are expressed by the term of technical status $AT(i,r,s)$. Furthermore, the technical status $AT(i,r,s)$ is composed of three different terms as follows:

$$AT(i,r,s) = atf(i) + atr(r) + ats(s) + atall(i,r,s), \tag{3}$$

where $atf(i)$: Technical status of shipping good *i*, $atr(r)$: Technical status of shipping from region r, $ats(s)$: technical status of shipping to region *s*, $atall(i,r,s)$: Intersectional technical effect of shipping good *i* from region *r* to region *s*. From these technical expressions, the transportation price changes occurring as a result of the detour can be reflected in $PT(i,r,s)$, and this indicates that technical changes occur in shipping industries at the same time.

4.2 Estimation of Transportation Costs

An increase in transportation costs can be a major trigger of global economic impacts and for this reason the background data used to calculate these costs should be collected carefully. In particular, in a case study of the Straits, it is crucial to estimate the number of vessels passing through the Straits and the additional cost incurred by each type of vessel as a result of detour. The calculation of international shipping cost divided by the volume of trading goods also represents information indispensable to the investigation of the impact of cost increases on each trading good.

A detailed survey of vessels in the Straits was conducted by JAMS (2006) between September 1 and November 30, 2004. These statistics are useful in that they classify both the size and types of vessels. In addition, the data has the advantage of the survey period being consistent with the global economic database (Badri and Walmsley 2008) used in this study. Fig. 6 shows the number of vessels classified by type and size. As consistent yearly statistics, Japan's Ministry of Land, Infrastructure, Transportation and Tourism (MLIT 2012) reports the total number of ships passing through the straits of Malacca and Singapore. In Fig. 7, the number of vessels and their types are compared with 2004 figures. There is a clearly increasing trend over the 10 year period. The largest increase is in the number of container ships. Yearly data has been estimated by vessel size by applying the proportion of vessel types observed in Fig. 6.

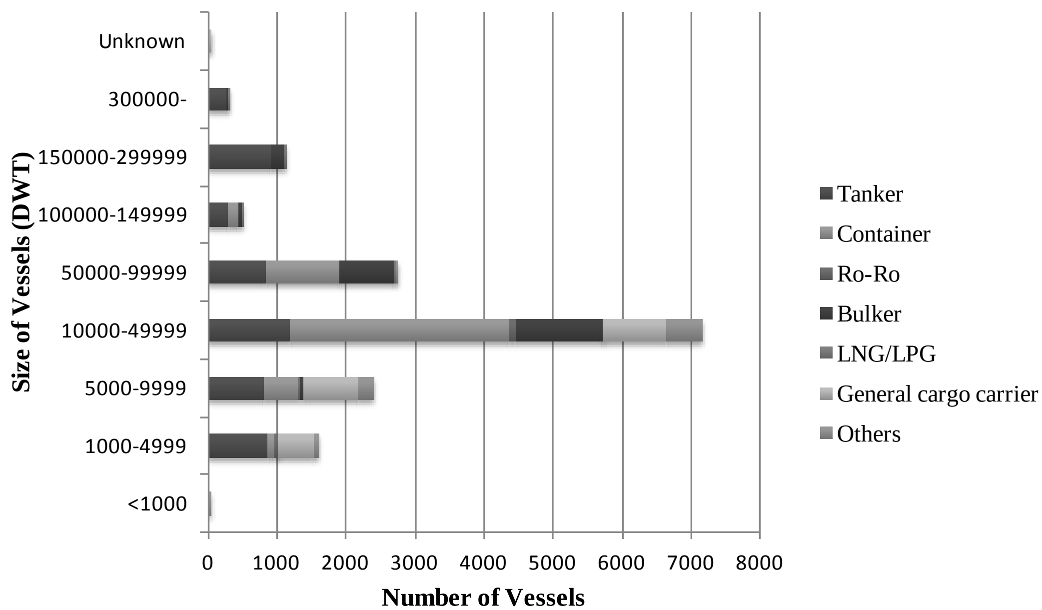

Fig. 6 Number of vessels by type over a two month period

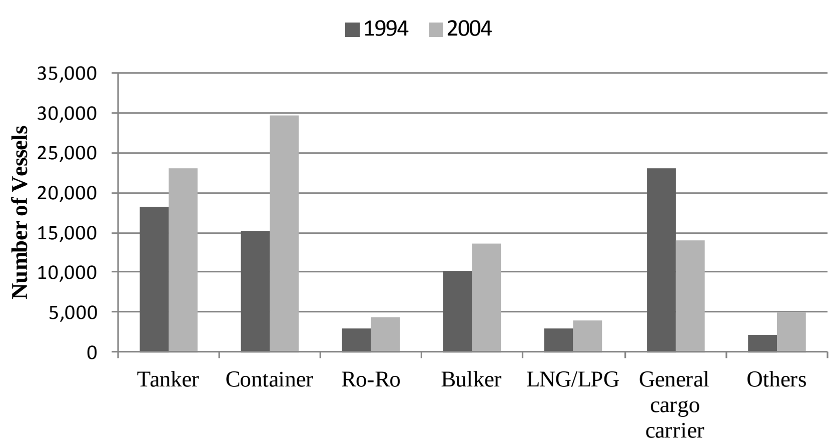

Fig. 7 Number of ships passing through the Straits of Malacca and Singapore annually

In order to establish the increased costs resulting from the detour of all ships, several assumptions must be made to compensate for that data not directly available. In a previous study of the Straits of Malacca and Singapore, Morisugi et al.(1992) focused on ship charter fees and bunker costs as primary sources of cost increase. For example, the study estimated that for an oil tanker of 230,000 DWT the charter fee is $22,000/day, and the bunker cost is $27,000/day. The daily charge for an extension of the ship, therefore, is $49,000. However, these costs are in constantly fluctuation and may sometimes change rapidly due to global economic investment booms and depressions, particularly in recent years, and it is therefore necessary to elaborate the ranges of these costs to some extent.

Another problem is that daily charter fees are not available for container ships and some other ships. One approach is to estimate a charter fee from the available capital costs (construction costs) of different ship types. It is reasonable to assume the expected return is similar if the capital costs are similar. The relationship between construction costs and daily ship charter fees for bulk carriers have been investigated from this perspective. Fig. 8 illustrates the relationship between ship charter fees and construction costs for the last ten years for bulk carriers using published data sources (MOL 2012; Clarkson 2008-2011). A relatively acceptable linear relationship between two indicators is shown and this relationship has been adopted for the estimation of the ship charter fees for those vessels for which construction costs are available. There is also a limitation in using the construction cost approach to obtain the accurate charter cost, because these costs are not available for or do not exactly match all the different vessel sizes and types shown in Table 4. The representative or alternative construction costs data for such vessels have been estimated by allocating similar and available bulk carrier vessel sizes as shown in Table V.

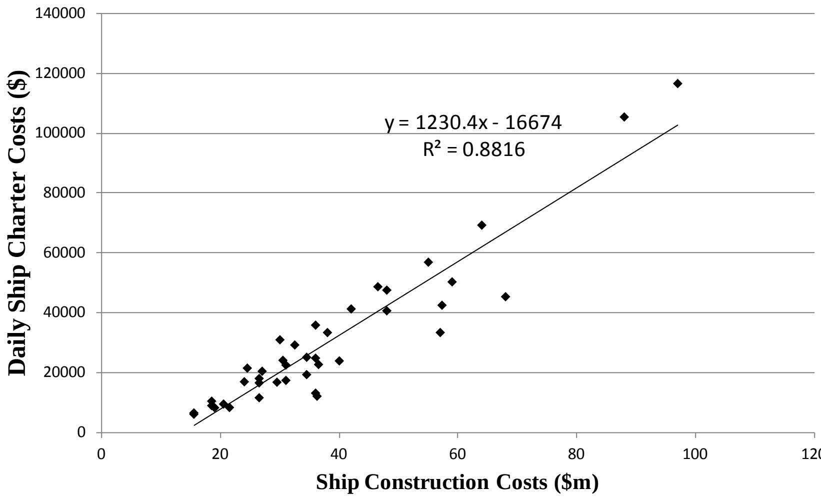

Fig. 8 Relationship between average ship charter costs and ship construction costs (Bulk carrier)

Table 4. Allocation scheme of corresponding bulk carrier size data for different types of ships

	<1,000 (dwt)	**1,000-4,999**	**5,000-9,999**	**10,000-49,999**
Tanker	-	Handy 51,000dwt	Handy 51,000dwt	Handy 51,000dwt
Container	-	Container 725teu	Container 1,100teu	Container 1700-3500
Ro-Ro	-	Ro-Ro 1,2-1,300Lm	Ro-Ro 1,2-1,300Lm	Ro-Ro 2,3-2,700Lm
Bulker	-	Handysize 35,000dwt	Handysize 35,000dwt	Handymax 57,000dwt
LNG/LPG	-	-	-	LPG 24,000m^3
General cargo carrier	Container 725teu	Container 725teu	Container 1,100teu	Handysize 35,000dwt
Others	Container 725teu	Container 725teu	Container 725teu	Handysize 35,000dwt
	50,000-99,999	**100,000-149,999**	**150,000-299,999**	**300,000<**
Tanker	Panamax 75,000dwt	Aframax 115,000dwt	Suezmax 157,000dwt	VLCC 320,000dwt
Container	Container 4,500teu	Container 6,350teu	-	-
Bulker	Panamax 76,000dwt	Panamax 76,000dwt	Capesize 180,000dwt	Capesize 180,000dwt
LNG/LPG	LPG 60,000 m^3	LPG 82,000 m^3	LNG 147,000 m^3	LNG 147,000 m^3
General cargo carrier	Handymax 57,000dwt	-	-	-
Others	Handymax 57,000dwt	-	-	-

The last cost item to be estimated is the bunker cost, which is the result of the combined effect of fuel price and fuel consumption. Akakura and Sema (2010) analyzed the fuel consumption rate of bulk carrier ships and obtained a good statistical correlation between the ship size of bulk carrier and the fuel consumption rate, as follows:

$$Y=0.000238X+16.7 \ (R^2=0.90), \tag{4}$$

where Y: Fuel Consumption (MT/Day), X: Vessel Size (DWT(10^3)). Assuming that the fuel consumption rate depends on vessel size and further that the speed of the vessel is fixed, this statistical relationship can be applied to all types of vessel. For bunker cost, this study adopted yearly average bunker cost statistics as summarized by the International Energy Agency (IEA 2011) and set the price statistics of CT380 (Singapore) as representative bunker costs.

Fig. 9 gives the estimated average costs for a one day trip per one ship for three different benchmark years. 2004 is the baseline case, which is consistent with global trade statistics, and 2002 and 2007 are the years where the ship charter costs and bunker costs are the lowest and highest respectively between 2001 and 2009. In the case that all the ships were required to use the Lombok Strait, it is estimated that each journey would take an addition72.7 hours (METI 2005). The following case studies assume that the shipping costs increase as a result of the additional 72.7 hours of voyage time.

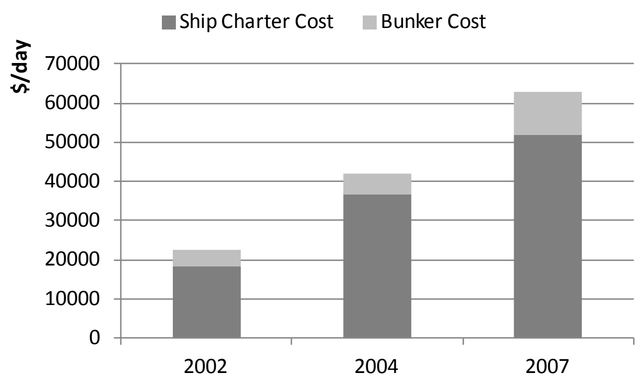

Fig. 9 Estimated average costs for each single additional day per one ship

4.3 Results and Discussions

4.3.1 Baseline Case

Since data sets on vessels and global trade from 2004 are available, we set up the case study using 2004 data, using an economic model with default GTAP model parameters, and adopted as the baseline case the scenario that both the Straits and their Ports were shut down. Fig. 10 shows the results of economic losses for the baselinecase in terms of equivalent valuation (EV), a measure of welfare in the region. The Lombok Strait plays the role of the alternative route, which would cause an additional 72.7 hours for shipping per voyage. There is the possibility that small vessels would be able to pass though the Sunda Strait, which provides a shorter route compared to the Lombok Strait route, but for the purposes of this study it is assumed that all vessels pass through the Lombok Strait, in consideration of the increasing trend of large-size vessels. In total, the average additional sea transportation cost becomes 5.76 %.

Fig. 10 shows that a closure of the Straits would become a major source for of wide-spreading impacts on all relevant regions, especially China, the EU and North America. The closure of the Port of Singapore would cause additional severe impacts on the economy in Singapore but only little impact on the economies of other countries. The total losses in the case of the closure of the Straits and the Port of Singapore are calculated at $19.4bn, with $14.7bn the total in the case of the closure of the Straits only. It may be noted that Morisugi et al. (1992) estimated figures of $84.3bn between 1966 and 1985 ($4.2bn/year), and anticipated $257.3bn for the next 20 years ($12.9bn/year) in consideration of increasing trends of bulk and petroleum vessels. The method adopted by Morisugi et al. (1992) is different to that applied here and it is therefore difficult to compare results, but the economic impacts given in this study is estimated are more severe, partly because the CGE model used in this study adopts the impacts on the world economy through price changes.

Direct reasons for welfare changes are increases in commodity prices and decreases in regional income. For example, in the case that both the Straits and the Port of Singapore are closed, a simple average of world price indices among different commodities, excluding sea transportation, increases by 0.03%, and the world price index for the sea transportation sector increases by 6.99%. At each country level, the increase in price index varies between 0.10% and 0.27%, while on the other hand, regional income decreases in many of the counties. Some of the countries and regions, such as the EU, Japan and North America record slight gains, but not as much as the price increase.

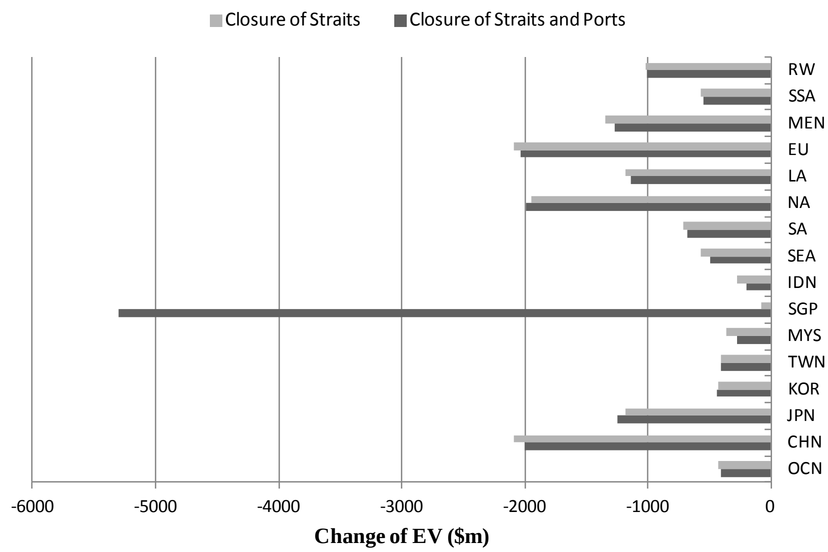

Fig. 10 Economic impacts of the closure of both Straits and port facilities (Baseline case: increase of 5.8% margin (international transportation) costs) compared with the impacts of the closure of Straits only (Standardized by annual disruption)

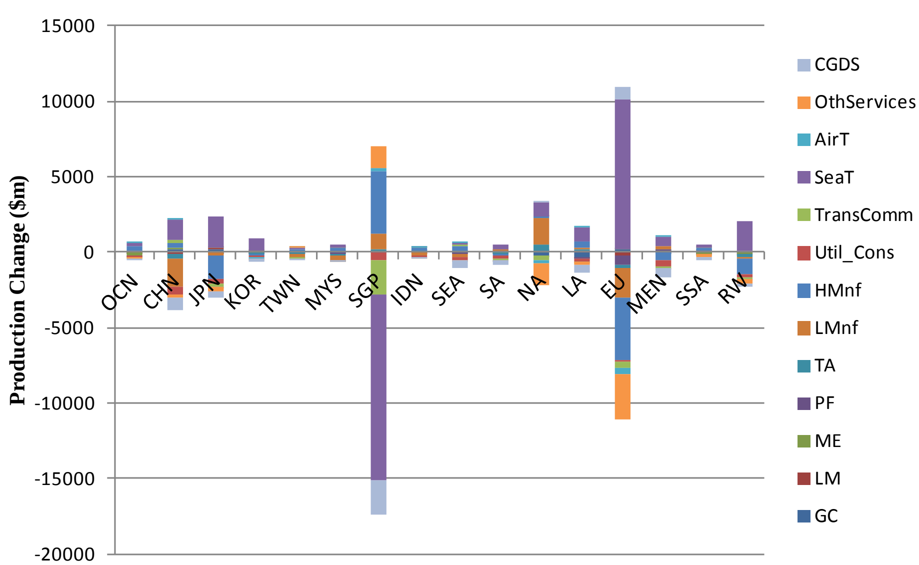

Fig. 11 Production changes among different sectors in each region

Fig. 11 shows changes in production ($m) in each sector of each country. Whereas a large drop of production in the sea transportation sector is observed in Singapore, air transportation functions partially as an alternative sector. EU also increases production of sea transportation and substitutes those international shipping services originally provided from Singapore. Japan and China also cover part of the drop in world shipping services. Changes in production between sectors and countries are determined not only by price changes but also by production capacity and productivity in each country. In addition, substitutions look to be executed smoothly because of the flexibility of capital movement. In actuality, as the Institute of Shipping Economics and Logistics (ISL 2010) reports, "as of July 1, 2010, the top 10 shipping nations controlled over 69 per cent of the total world merchant fleet deadweight tonnage (ships of 1000 gt and over)", and among those top 10 countries, 47 % of the merchant fleet deadweight tonnage was handled by four European countries in 2010, based on ISL statistics.

Note that it is a limitation of this analysis that more detailed information is not available in the sea transportation sector. Normally, the sea transportation sector consists of port facilities, vessels, and vessel construction industries. In addition, the locations of port facilities are not taken into account. Most of the alternative services to the Port of Singapore would be executed by substitute ports within Asia. In this case, a hare of international shipping service provided by the EU could be reduced. Such effects go beyond the limitations of this analysis; a more detailed segregation of the sea transportation sector and the consideration of geographical locations of ports are required to advance this research.

4.3.2 Sensitivity Analysis

(1) Transportation costs

Transportation costs are one of the key variables which affect wide spreading impacts. These costs fluctuate constantly and significant changes can be observed in short periods, particularly in recent years. In order to investigate changes in transportation costs, as the upper and lower cost cases, transportation costs for 2008 and 2002 were examined in addition to those of 2004. Increases in transportation costs were 8.62% for 2007 and 3.10% for 2002, respectively.

Fig. 12 compares the results of all the cases and indicates how impacts are significantly different among all countries except Singapore, where the disruption of the port facility dominates the impact of transportation cost changes. With the exception of Singapore, the EV changes are: $-7,357m in 2002, $-14,103m in 2004, and $-21,293m in 2007. In this range of changes in transportation costs, an almost linear relationship can be seen between transportation costs and economic losses. That is, in many countries, as the transportation cost doubles, the economic losses also doubles.

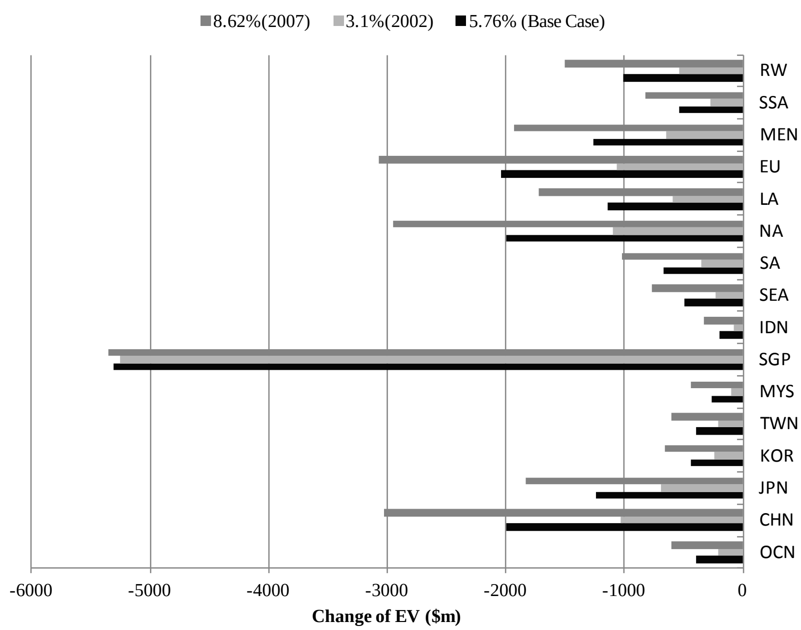

Fig. 12 Increases in transportation costs and economic losses

(2) Effects of Capital Movement

In the baseline case, it is assumed as a default that capital can be moved, but it is more likely that capital movement cannot be smoothly executed in a short period. Fig. 13 compares the case with and the case without capital movement for a sensitivity analysis. In the case that capital movement is restricted, the first point would be the enlargement of welfare losses in Singapore. This is mainly caused by the loss of substitution by other transportation services. The second point would be the result that losses are reduced in those other countries which substitute international shipping services. The major reason for this would be the increase in international shipping costs as a result of the loss of substitution options caused by the restriction of capital movement among sectors. In this way, capital movements work to spread losses throughout the world and to reduce the damages incurred by the most significantly affected country (Singapore). In total, loss is decreased from $-17,947m to $-19,407m by not allowing capital movement.

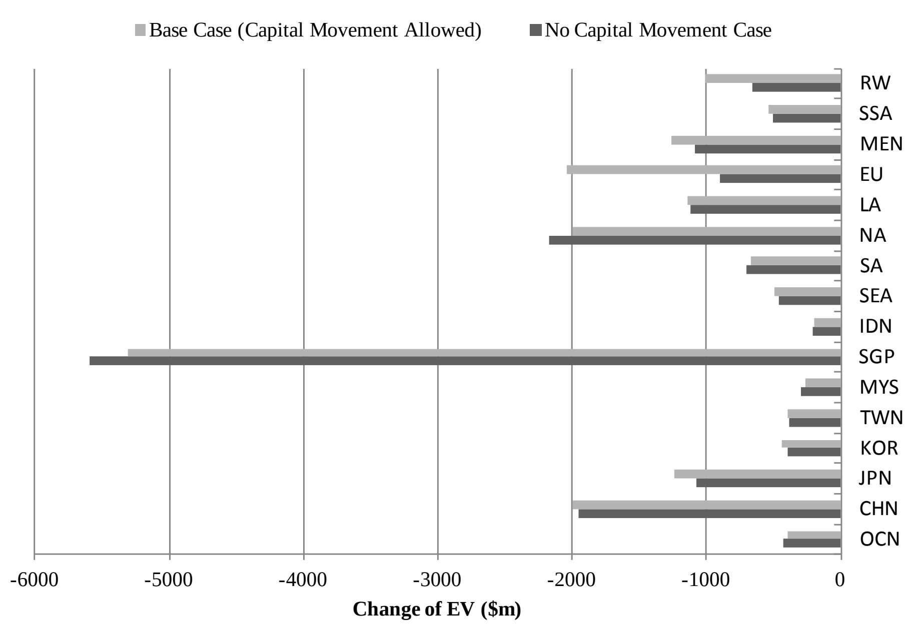

Fig. 13 Effects of capital movement

(3) Effects of CES Parameters

Fig.14 illustrates a comparison of the case studies where the values of the CES parameters for domestic/imported goods allocation and regional allocations for foreign goods are changed. The values of these parameters are individually set to half of the original values. Compared to the baseline case, these changes tend to increase the damages to Singapore and reduce the losses of the EU, Japan and China, as is seen in the capital movement case. However, in contrast to the capital movement case, the total losses increase from \$19,408m to \$20,855m in the “Regional allocation: half values” case and to \$29,911m in the “Import/domestic allocation: half values” case. The case in which transportation services in Singapore cannot be substituted by services from other regions results in significantly more impact on other industries, especially those located in Singapore.

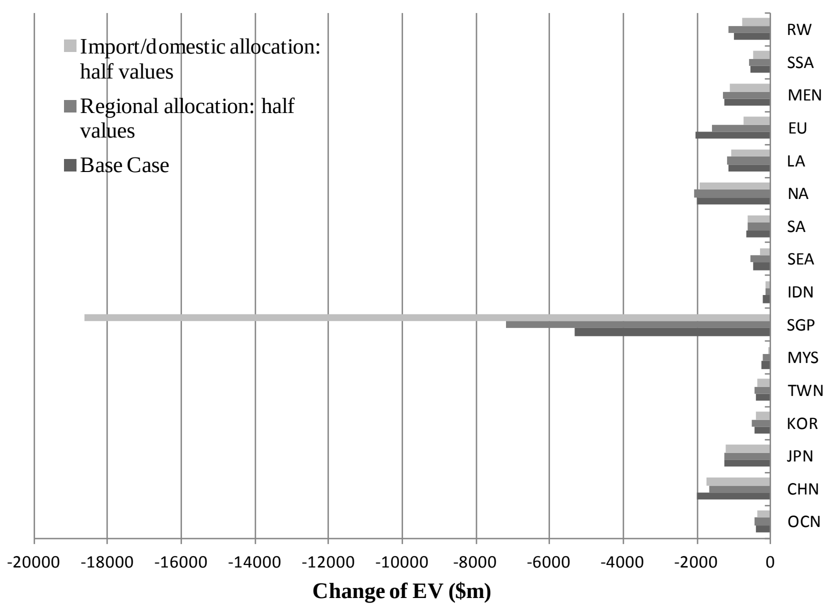

Fig. 14 Sensitivity Analysis (Changes of CES Parameters)

(4) Policies of price changes in transportation costs

The final investigation concerns pricing policy/strategy in the sea transportation sector. The baseline case assumes that world international shipping costs increase at the same rate to cover all detour costs. Another possible strategy for shipping companies is to charge extra shipping costs only to those trading goods which pass through the Straits. In other words, detour costs are not directly reflected in the transportation costs of bilateral trades which do not pass thorough the Straits, such as trades between Latin America and North America. In the case that all detour costs are reflected in the shipping costs for the goods passing through the Straits, the shipping costs for those goods is estimated to increase by 48.17%. Fig. 15 shows that this increase significantly affects most of Asia, the Middle East and North Africa, and the EU. Some regions experience increased profit, but total global losses increase from $-19,407m to $-24,520m.

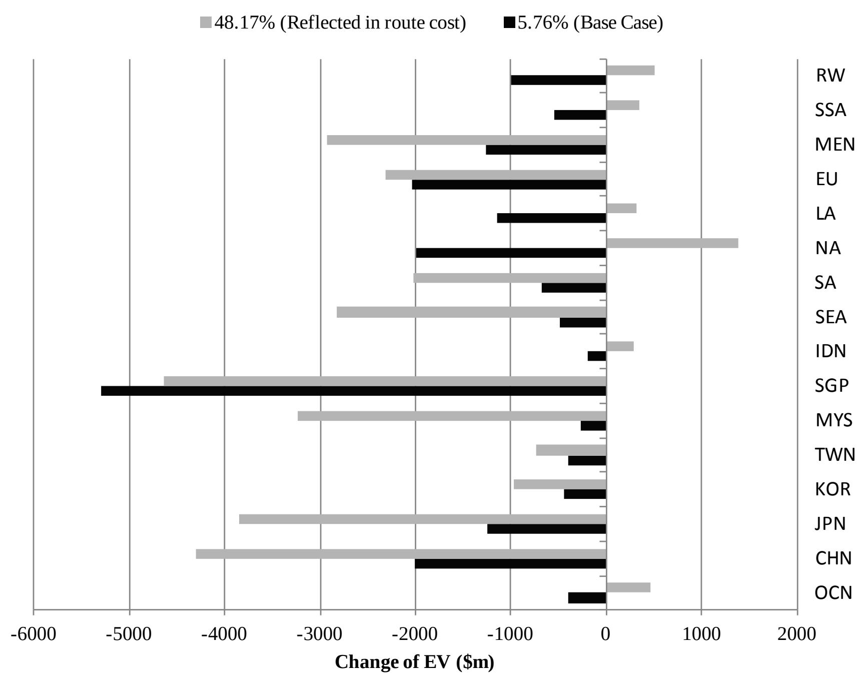

Fig. 15 Sensitivity Analysis **(**Policies of price changes in transportation costs**)**

5. CONCLUSIONS

This study proposes a prototype risk assessment case study for "maritime global critical infrastructures", focusing on the economic impacts of disruption. Due to the globally shared and intensively used nature of such infrastructure, the disruption of any MGCI would result in significant trans-boundary impacts across the globe. Risk reduction efforts, such as the development of alternative infrastructures, are required for MGCIs. However, as with the deficits of MCGI risk governance, described in the previous study, the assessment of externalities, such as environmental, societal and economic impacts, remain necessary tasks and has not yet been fully conducted. As a result, the share-burden among stakeholders for preventing such a disruption continues to be ambiguous.

To provide, therefore, a reference case model for assessing economic impacts, one of the significant externalities related to MGCIs, this study conducted an in-depth analysis of the case of a chemical facility explosion scenario at the Straits of Malacca and Singapore. For this case study, a database of chemical facilities was constructed and transportation costs were estimated from various types of vessel and bunker costs, after which the chemical explosion model and global economic impact assessment model were integrated to determine those regions physically and economically affected, as well as to consider their economic losses. In the analysis, the disruption of port services and detour costs were considered as the primary shocks to impact the world economy, after which trade patterns and total economic losses were estimated based on a global CGE model.

The results show that economic impacts are severe in Singapore as a result of damages to the sea transportation sector and that the impacts spread to the rest of world through increases in transportation costs. It has also been demonstrated that some elements of the shocks may be absorbed through the adaptive behavior of other economic sectors, such as substitutions of goods and services, labor and capital movement to sectors where there is greater scarcity. In order to interpret the effect of key parameter values, the range of economic impacts were also captured by conducting several sensitivity analyses on transportation costs, capital movement, substitution parameters, and the cost increase strategies of shipping companies. In this case study, the total economic costs are estimated as ranging from around $13,000m to $28,000m depending on certain key parameters. In particular, the results can drastically change as a result of abrupt increases in oil costs and in the pricing strategies adopted by shipping companies, such as which route price they will increase. As such, mitigation measures should be discussed in consideration of the fluctuations of key economic indicators and in the context of all stakeholders including shipping companies.

In this way, this paper provides a prototype risk assessment model and case study of MGCI, and the results derived thereof can be used to share the critical importance of target infrastructures on a global scale, and to establish cost-effective countermeasure investments. The distribution of losses in each country may be reflected in a share-burden scheme for such countermeasure investments. However, more work is necessary to improve this approach. In particular, geographical location and the advantage(s) of alternative infrastructures are not considered in models and in data and the values of parameters, such as substitution parameters, require more thorough investigation. For example, Singapore provides high quality kerosene for air transportation through its Strait and Port, which is likely less easily substituted than other goods and has potentially significant secondary impacts in the event of distribution disruption. Stakeholder workshops based on the model and case study adopted in this paper would also help to develop additional scenarios and to foster the development of the risk governance scheme.

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